H2020-MSCA-RISE-2019-GA641540, SK2HK

HP-Ge detectors for controlling the very low levels of Radioactive Contaminations in the Gadolinium salt needed at the Super-Kamiokande Gd experiment

A global effort by Boulby Underground Laboratory, Canfranc Underground Laboratory and Kamioka Observatory

Presented by *Luis Labarga*, *U. Autonoma Madrid*

Main actors:

Boulby: E. Meehan, P. Scovell, M. Thiesse (U. Sheffield)

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Kamioka (KObs): H. Ito (ICRR, now at Tokyo U Science), K. Ichimura (ICRR, now at U. Tohoku)

++ M. Ikeda, H. Sekiya (ICRR), Y. Nakajima (ICRR, now at Phys. Dept. UT), P. Fernández (UAM, now at DIPC), M. Vagins (IPMU, UT), S. Ito (U. Okayama, now at KEK) Y. Koshio (U. Okayama), ….

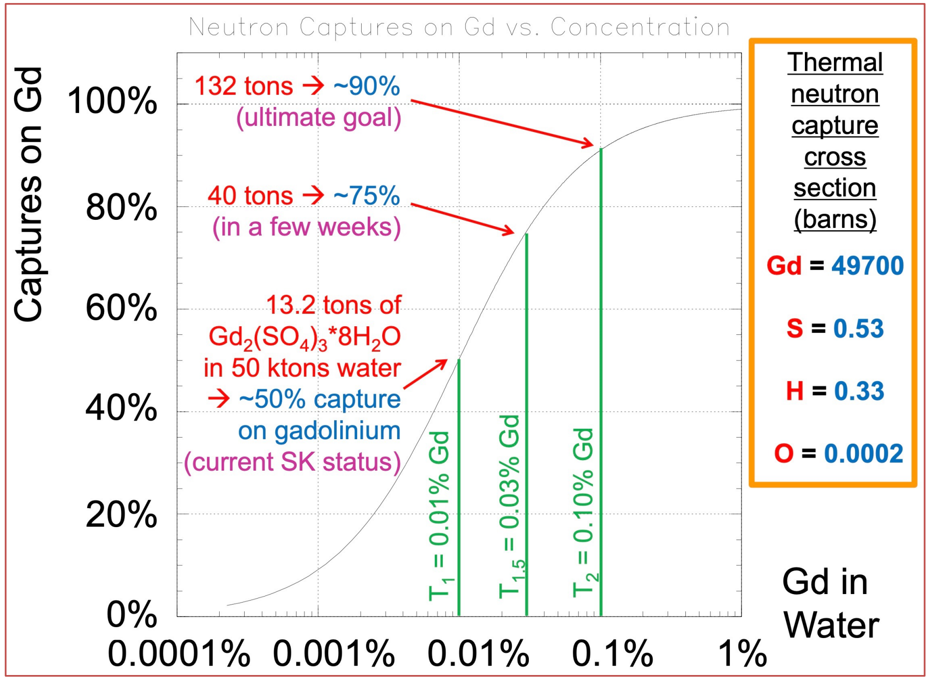
UGAP2022 ***"Unraveling the History of the Universe and Matter Evolution with Underground Physics"***

2022/06/13 *Tokyo University of Science +* Online

Introduction / Outline

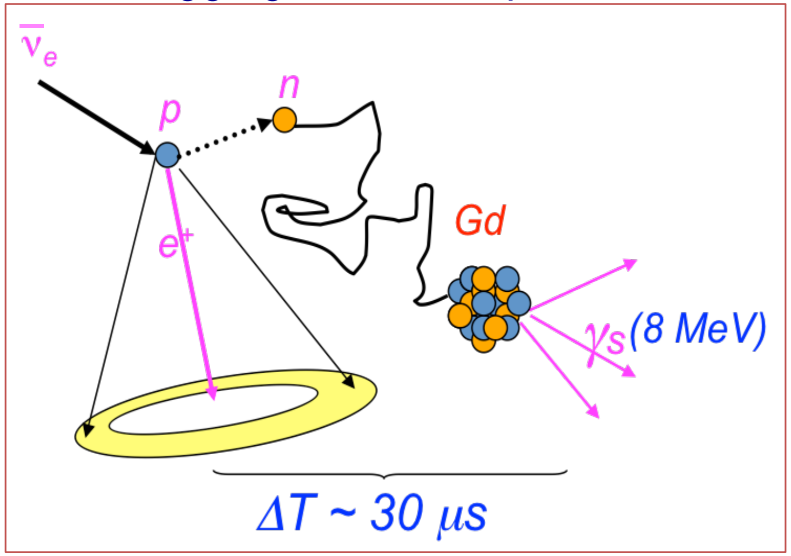
- The Super-Kamiokande Gd project aims to improve the insight of SK into the Universe and its history. Main target is the discovery Diffuse Supernova Neutrino Background (DSNB)
- It needs of many tons of Gd salt; they must have very low RI levels not to jeopardize relevant SK physics and the main SK-Gd physics goals. Also carefull with light emitting contamination
- Gd "out of the shelf" in the market is "hot" → a new purification process is mandatory
- And thus is a procedure to measure/control those extremely low RI Gd. Base systems:
  - ICPMS only for very long lifetime RI (and other stable contaminants)
  - HP Ge detectors for all RI (that produce γs in their decays)
- the Gd salt is produced in many batches (typically 2 x ton); all must be screened. 27 batches screened for T1;
- but HP Ge techniques are slow → global effort needed: Boulby Underground Laboratory, Canfranc Underground Laboratory and Kamioka Observatory involved.
- Results, discussion etc.

Super-K Gd: neutron tagging by Gd capture

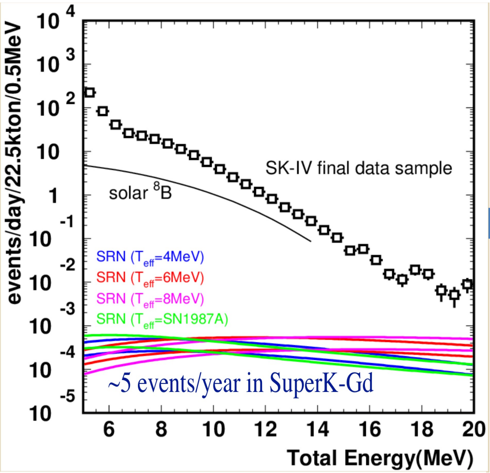


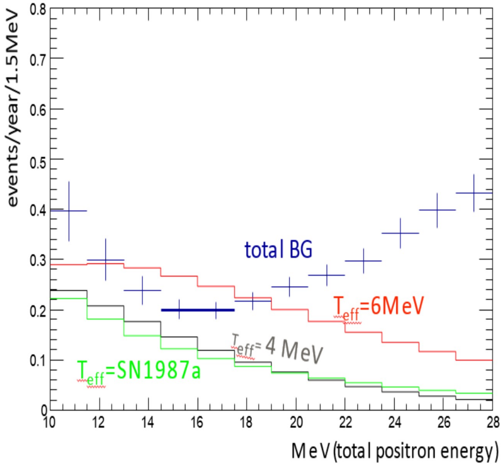
See M. Vagins' talk tomorrow

➔ $\bar{\nu}$ tagging at inverse β reaction



➔ access DSNB after very much reduced background





In addition:

- high precision solar-ν elements from available reactor νs
- SN early warning from Si burning νs
- Much improved background at proton decay searches
- …

Super-K Gd: neutron tagging by Gd capture

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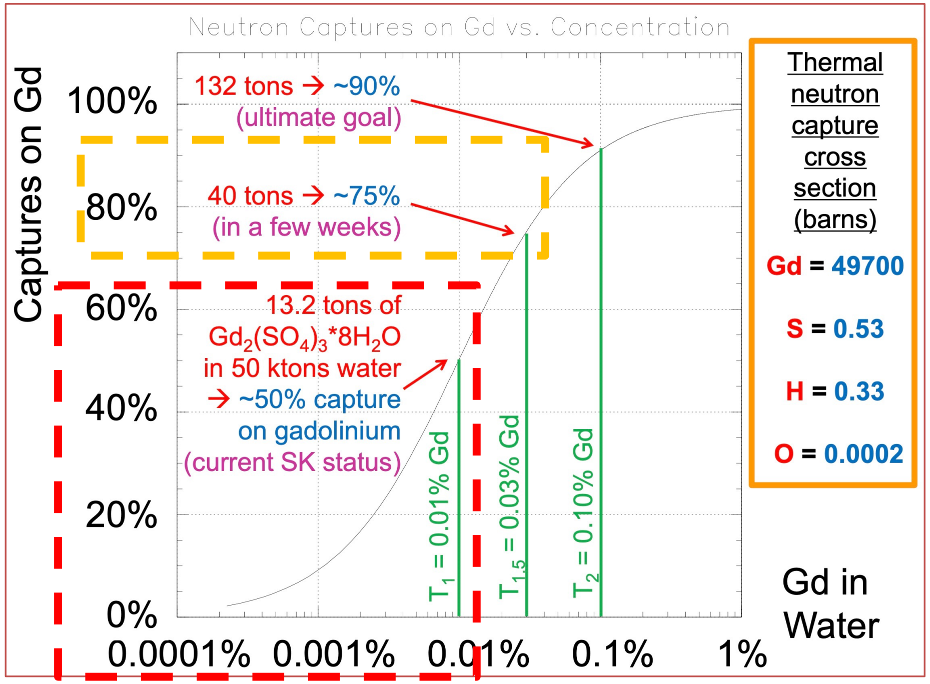

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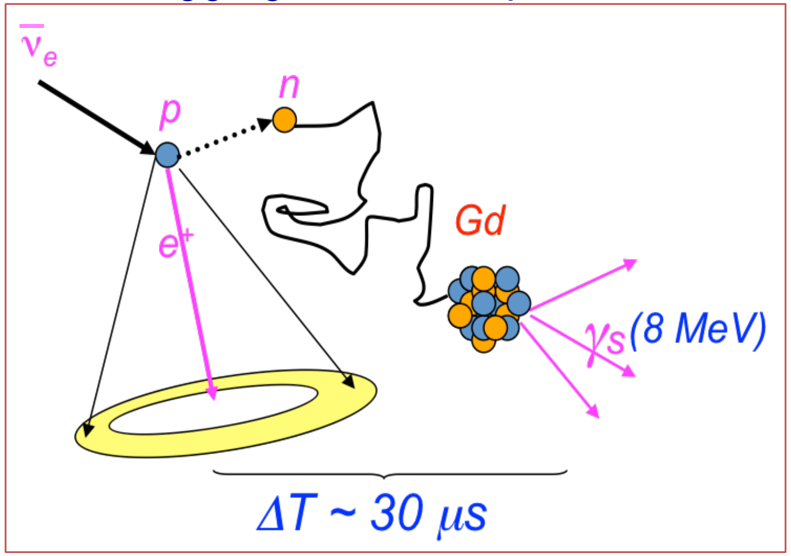

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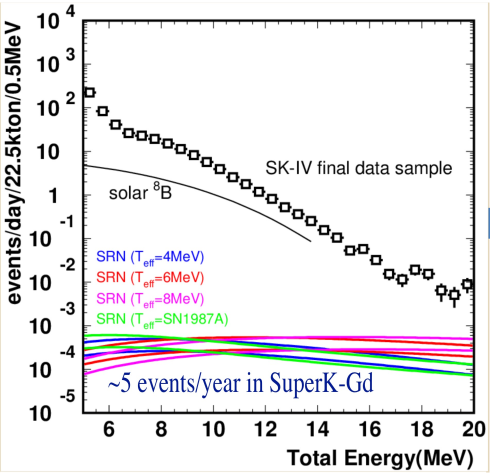
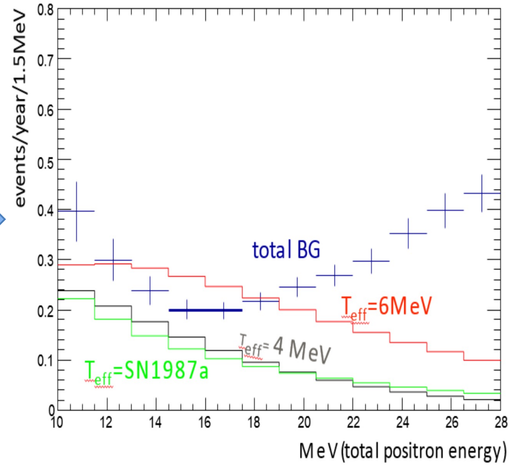




In addition:

- high precision solar-ν elements from available reactor νs
- SN early warning from Si burning νs
- Much improved background at proton decay searches
- …

In SK-Gd,

radioactive contamination in the Gd salt is an issue

- In SK-Gd many tons of Gd salt [$Gd_2(SO_4)_3 \bullet 8H_2O$] will be uniformly dissolved along the whole SK volume, thus it will any RI contamination in the Gd salt
  - → this might jeopardize relevant low energy SK physics
  - → and the main SK-Gd physics goals (mostly low E physics as well)

➔ The Gd salt must have the corresponding very low RI levels

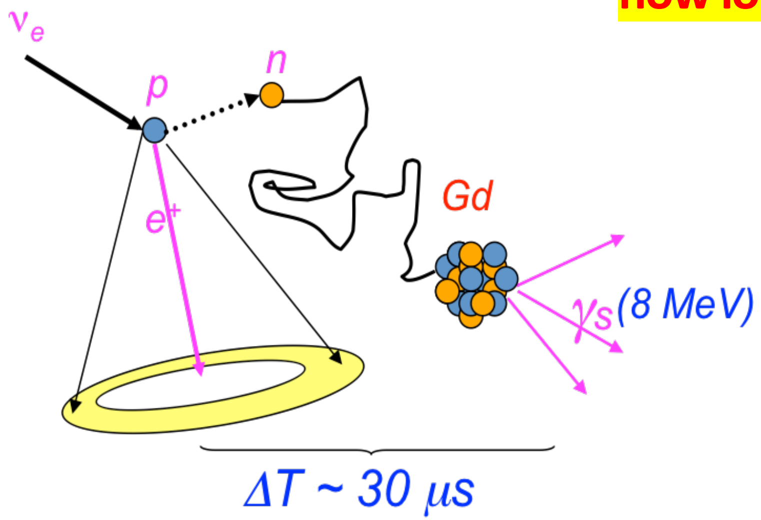
how low RI is needed (I) ?

Main radiation produced by radioactive isotopes from contaminations:

- **S**pontaneous **F**ission (SF)→ neutrons, **γ**s (these can have significant energy)
- **α** decays → **α** ($^4He_2$) particles → neutrons from (**α**, n) reactions
- **β** decays → **β** particles (electrons) rather dangerous
- nucleus stabilization after decay processes → **γ**s (less energetic than SFs)
- special care when **γ**s, neutrons, **β** are produced in coincidence

how low RI is needed (II) ?

Background for DSNB



^{238}U Spontaneous Fission:

- coincidence n – γ (Eγ>10 MeV)
- irreducible background !
- fortunately not a serious issue

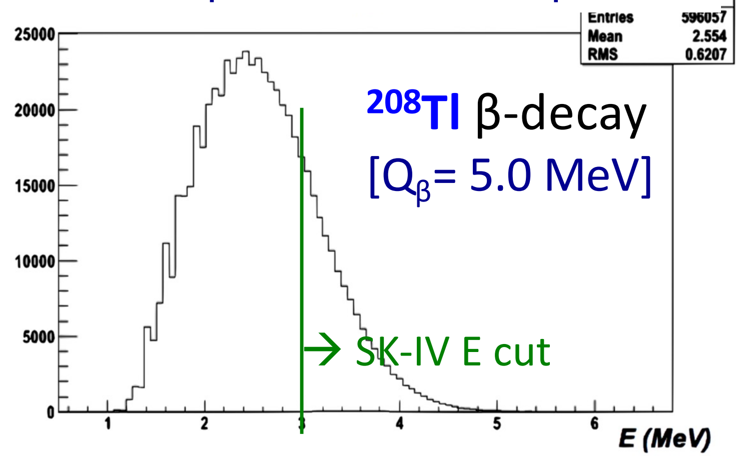
solar-ν in accidental coincidence with neutrons or βs from radioactivity very suppressed (solar final E>10 MeV)

Background for lowest Energy solar ν

βs from ^{232}Th (^{208}Tl, ^{212}Bi), ^{238}U chains (^{214}Bi)

- very severe bkg. source

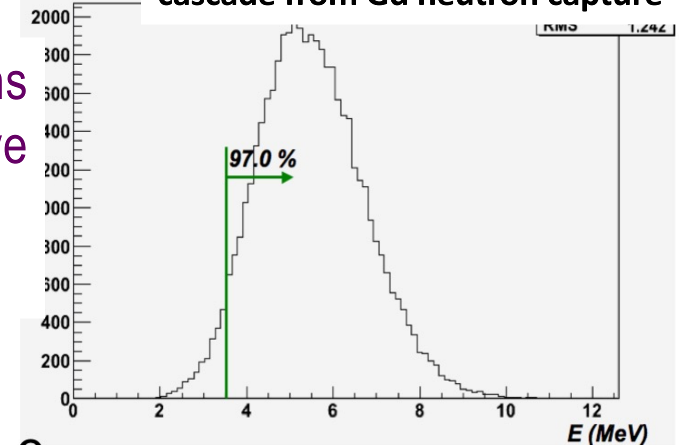
Rec. E spectrum in SK of βs ^{208}Tl



Gd captures of neutrons produced by the radioactive contamination

- sizable but less severe

approximate E spectrum of gamma cascade from Gd neutron capture



how low RI is needed (III) ?

P. Fernández Menéndez, Ph.D. Thesis UAM 2017

DSNB

- Expected signal at SK: ~5 events / year / FV
- Estimated bkg. from ^{238}U Spontaneous Fission: ~ 0.12 [**γ** (E**γ**> 10.5 MeV) + 1 **n]** / year / FV / **mBq**

Low energy solar neutrino:

- Approximated solar neutrino candidate event rate at SK: ~260 candidates / day / FV
- Estimated background solar neutrino candidates at SK:
  - Neutrons from (**α**, n) on Oxygen (**α** from U isotope decays): ~ 6 bkg. candidates / day / FV / **mBq**
  - Th / Ra (**β**, **γ**): **~ 3 x 10^3 bkg**. candidates / day / FV / **mBq**

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 30
	^{227}Ac / ^{227}Th	-	< 30

But, how clean Gd can you get from regular world market ?

$Gd_2(SO_4)_3$ "regular market" survey: radioactivity contaminations *(~2015)*

Chain	sub-chain	Co. A USA 09/04	Co. A USA 10/08	Co. B China 12/08	Co. A China 13/02	Co. B China 13/03	Co. A USA 13/08	Co. D China 13/07a	Co. D China 13/07b	Co. A USA 14/02
^{238}U	^{238}U	51±21	<33	292±6	74±28	242±6	71±20	47±26	73±27	< 76
	^{226}Ra	8±1	2.8±0.6	74±2	13±1	13±2	8±1	5±1	6±1	< 1.4
^{232}Th	^{228}Ra	11±2	270±16	1099±12	205±6	21±3	6±1	14±2	3±1	2±1
	^{228}Th	28±3	86±5	504±6	127±3	374±6	159±3	13±1	411±5	29±2
^{235}U	^{235}U	<32	<32	<112	<25	<25	<32	<12	<30	<1.8
	^{227}Ac	214±10	1700±20	2956±30	1423±21	175±42	295±10	<6	<18	190±6
others	^{40}K	29±5	12±3	101±10	60±7	18±8	3±2	3±2	8±4	<5
	^{138}La	8±1	-	683±15	3±1	42±3	5±1	<1	<1	23±1
	^{176}Lu	80±8	21±2	566±6	12±1	8±2	30±1	1.6±0.3	<2	2.5±0.6

Units are mBq/Kg; limits are at 95% CL s work done mostly at the *Canfranc Underground Laboratory*

- **Rather dirty**
- **Superk-Gd could not afford those amounts of RIs**

Typical activities of salts in the market @2015:
(extracted from previous slide)

Physics based requirements

Radioactive chain	Part of the chain	mBq/kg	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	50	< 5	-
	^{226}Ra	5	-	< 0.5
^{232}Th	^{228}Ra	10	-	< 0.05
	^{228}Th	100	-	< 0.05
^{235}U	^{235}U	32	-	< 30
	^{227}Ac / ^{227}Th	300	-	< 30

must !

➔ **a new, non standard purification process is a must**

➔ successful R&D program by Nippon Ytrium Co. (NYC) and ICRR – U. Tokyo

– see the soon-to-be-published publication with all these works –

- this “very clean” [$Gd_2(SO_4)_3$ • $8H_2O$] needs to be produced in 0.5 ton batches;
- SK-Gd phase T1 : 27 batches total

In addition, the presence of fluorescent ions such as **Ce** may impact the detection of Cherenkov light.

➔ The concentration of **Ce** ions is also restricted in the $Gd_2(SO_4)_3 \cdot 8H_2O$ material: < 50 ppb

➔ **a procedure to measure/control those extremely low RI Gd at the 27 batches is also a must**

- those nuclides in radioactive chains which contaminate $Gd_2(SO_4)_3 \cdot 8H_2O$ may not be in secular equilibrium with their long-lived parents and daughters. Several techniques ought to be used:
  - high purity Germanium (HPGe) γ spectrometry to measure the activity of the early and late parts of all decay chains which could affect SK-Gd physics sensitivities.
  - inductively-coupled plasma mass spectrometry (ICP-MS) to measure the long-lived members of the U and Th decay chains (^{238}U and ^{232}Th isotopes). Also for **Ce**

- Special ICP-MS techniques* developed in KObs to reach SKGD sensitivities for ^{238}U, ^{232}Th isotopes
- Regular ICP-MS (KObs, UAM) can reach sensitivities well below the Ce limit

- HPGe γ spectrometry can also infer the activity of long-lived parent or daughters
- Only HPGe γ spectrometry is sensitive to the SK-Gd requirements for late-chain ^{238}U (^{226}Ra equilibrium) and the whole ^{235}U chain. It is also sensitive to late-chain ^{232}Th (^{228}Th equilibrium) **but** not to concentrations down < 0.05 mBq/kg. Typical reaches are instead ~ 0.2 mBq/kg

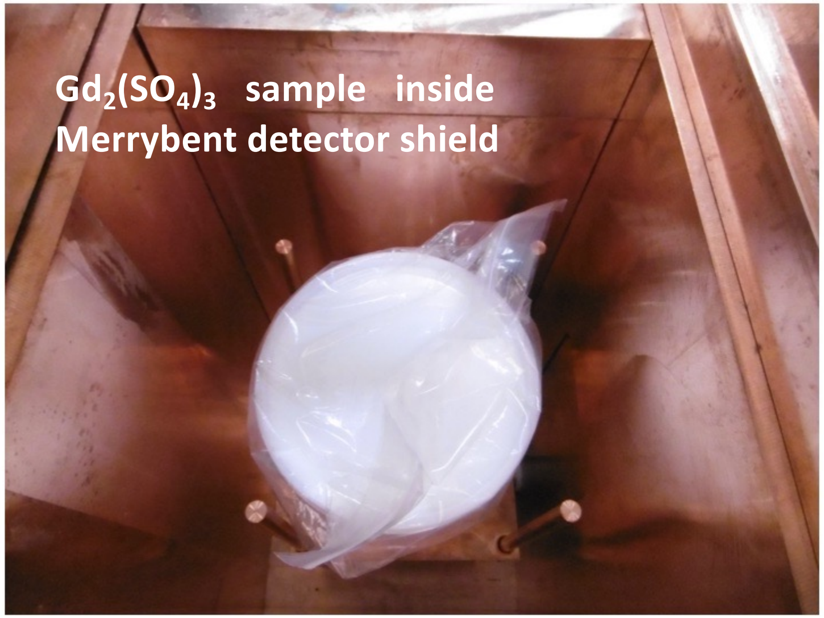
- HPGe techniques are slow → global effort needed: Boulby Underground Laboratory, Canfranc Underground Laboratory and Kamioka Observatory involved

(*) S. Ito et al. *PTEP*-2017-113H01

BOULBY UNDERGROUND LABORATORY

Main detectors for SK-Gd are Belmont and Merrybent, p-type, produced by Mirion (relative efficiencies 160% and 100%)

- Inside of shielding purged with boil-off N_2 gas.
- Gd is packed in Marinelli beakers 448G-E (Ga-Ma & Associates, Inc.)



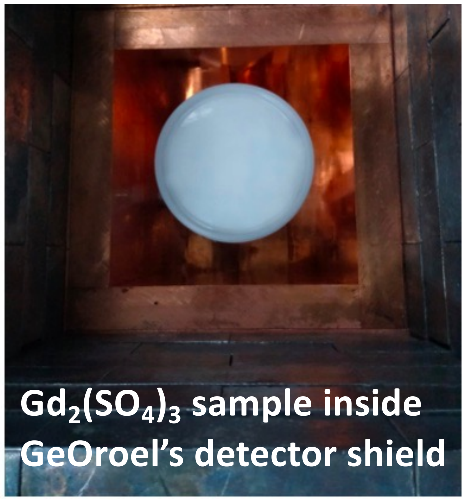
LSC

Laboratorio Subterráneo Canfranc

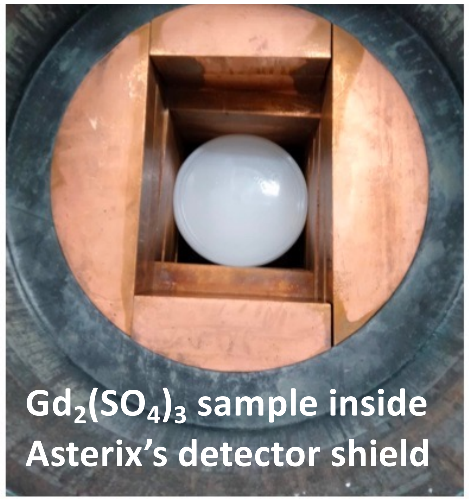
Canfranc underground Laboratory

- Main detectors for SK-Gd: Asterix and geOroel (both p-type by Mirion)
- Gd in Marinelli beakers (Ga-Ma and Asso- ciates, Inc. model 445N-E).
- extra layer of shielding made of methacrylate surrounding the lead shielding.
- slight over-pressure created inside the copper shielding by flushing ∼ 274 L/h of a mixture of N_2 and Rn-Free air.

ULBS laboratory in Hall C of LSC



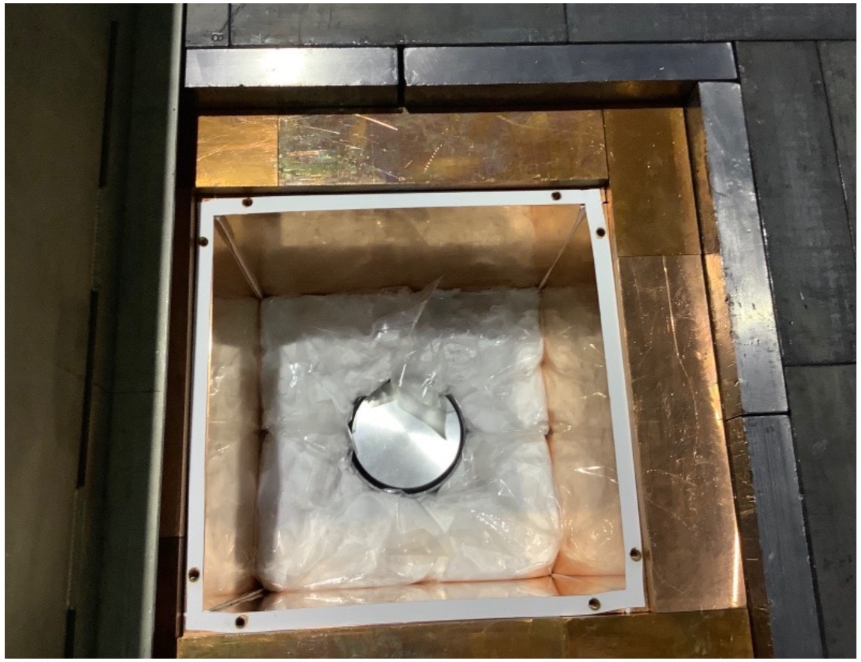
$Gd_2(SO_4)_3$ sample inside GeOroel's detector shield



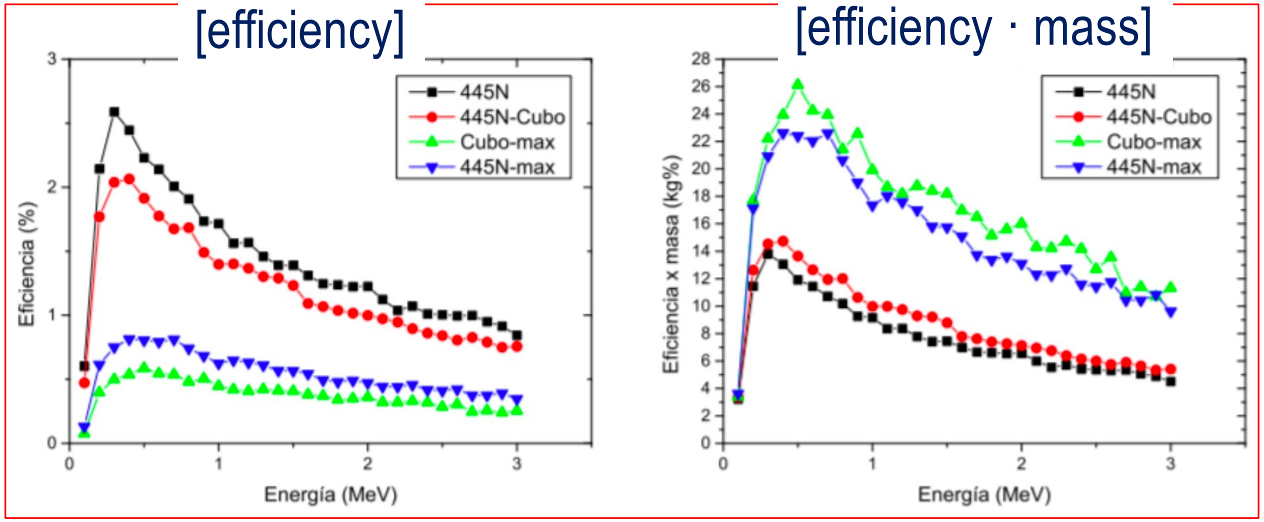
$Gd_2(SO_4)_3$ sample inside Asterix's detector shield two ways.

- A molecular recognition resin embedded in the "Empore Radium Rad Disk" (**) was used to adsorb Ra from the $Gd_2(SO_4)_3 \cdot 8H_2O$ and increase its concentration. Disk is placed on top Ge. (**) S. Ito et al. *PTEP*-2018-091H01, S. Ito et al. *PTEP*-2020-093H02
- Use large amounts of $Gd_2(SO_4)_3 \cdot 8H_2O$ (~10 Kg), filling the volume inside shielding → optimizes relevant variable for measurement [efficiency · mass]

Gd salt in 4 EVOH bags; Lab. – C Ge det.



Max. mass is at **cubic** *configuration. Others are Marinelli type configurations*



Cross-check by D. de Hoz, End-Degree-work, UAM 2021

Main HPGe detectors used for SK-GD T1 screening

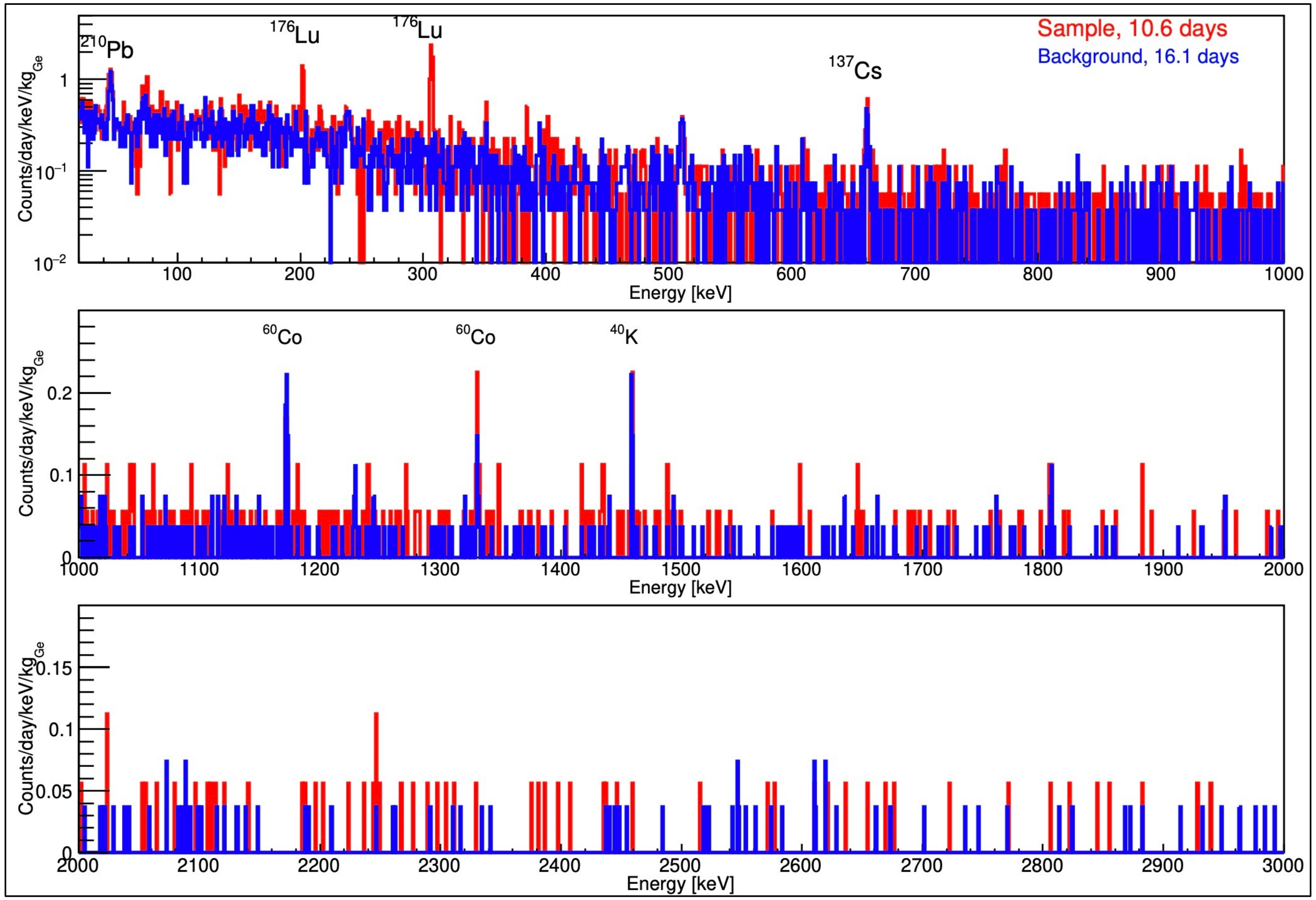
Lab	Detector	Mass [kg]	FWHM@ 1332 keV [keV]	COUNTS Integral 60-2700 keV	[/kg/day] ^{208}Tl, 2614 keV	^{214}Bi, 609 keV	^{60}Co, 1332 keV	^{40}K, 1461 keV	SK-Gd T1 total samples
BUGS	Belmont	3.2	1.92	90.0	0.12	0.67	0.47	0.58	8
BUGS	Merrybent	2.0	1.87	145.0	0.23	2.15	0.47	1.16	5
LSC	GeOroel	2.31	2.22	128.7	0.4	1.1	0.1	0.4	3
LSC	Asterix	2.13	1.92	171.3	0.2	0.7	0.3	0.3	11
LSC	GeAnayet	2.26	1.99	461.2	3.68	0.71	0.16	0.74	1
Kamioka	Lab-C Ge	1.68	2.39	104.5	0.1	0.4	0.4	0.3	22

Table 3: HP-Ge detectors used; main characteristics, background counts at relevant gamma and number of SK-Gd T1 samples screened in each of them

In general very low backgrounds at key gamma lines

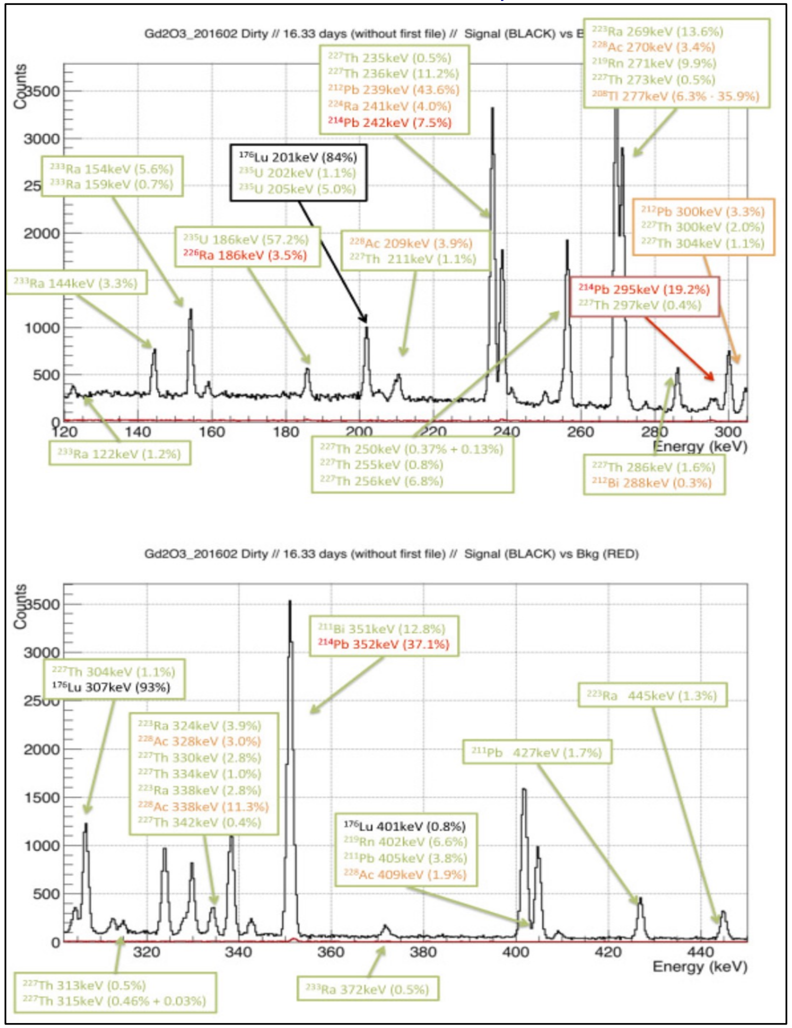
For illustration: measured **γ spectra** in a standard low RI Gd salt

Kamioka's Lab-C Ge detector



For comparison: γ spectra measured in a highly RI contaminated Gd salt

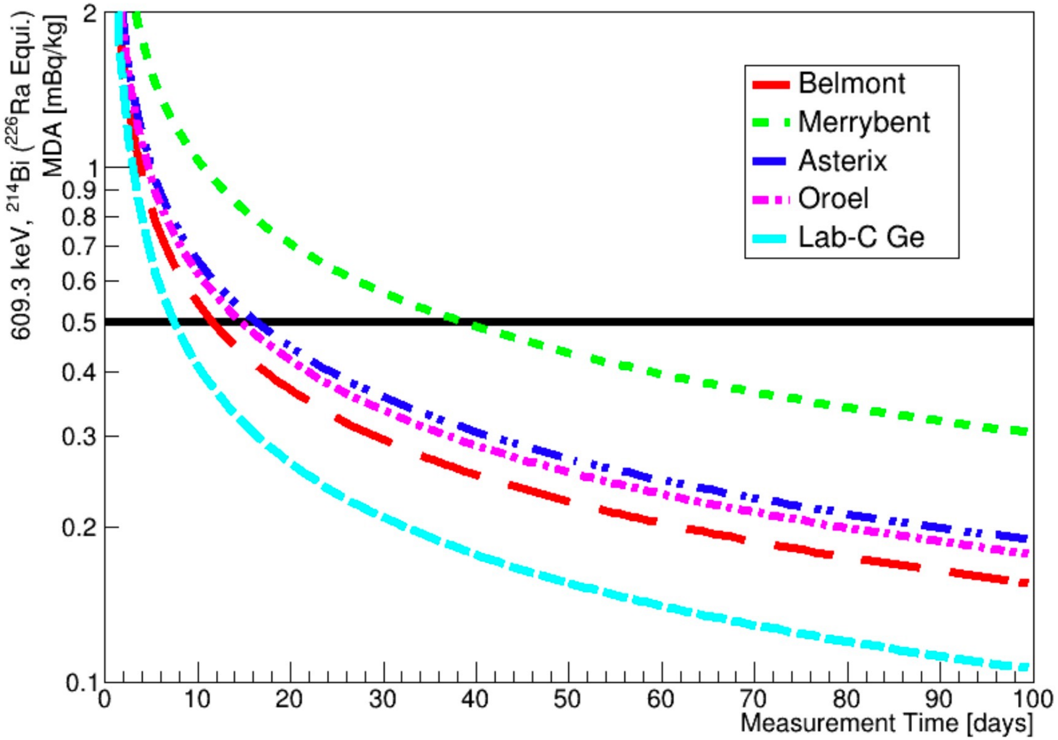
J. Pérez Pérez, Ph.D Thesis UAM 2017



Nothing ! Only ^{176}Lu (typical in rare earths) go above background

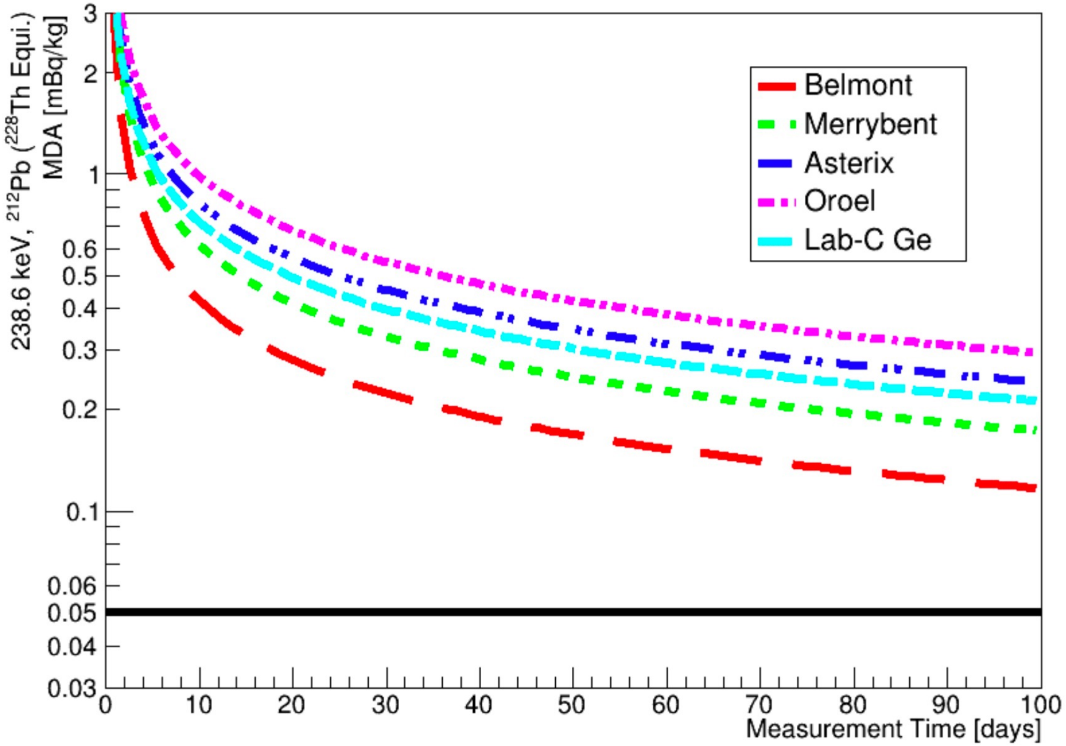
Minimum Detectable Activity of our detectors
(illustrated by two important γ lines)

609.3 KeV γ from ^{214}Bi (^{238}U chain-lower)



SK-Gd limits reached within "couple of weeks"

238.6 KeV γ from ^{212}Bi (^{232}Th chain-lower)

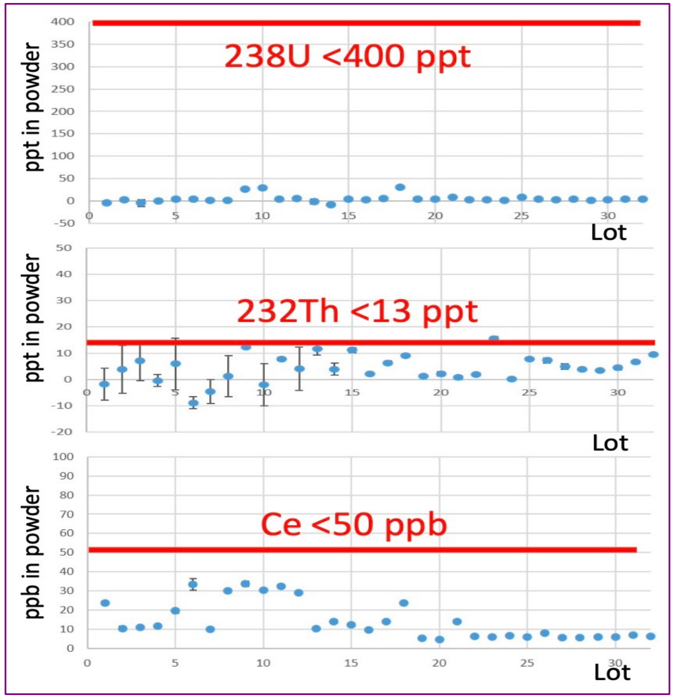


SK-Gd limits not reached

HP-Ge results (see additional materials for larger size)

Sample	Laboratory	Detector / Method	Activity (mBq/kg, 95% c.l.) ^{238}U: ^{238}U eq.	^{238}U: ^{226}Ra eq.	^{232}Th: ^{228}Ra eq.	^{232}Th: ^{228}Th eq.	^{235}U: ^{235}U eq.	^{235}U: $^{227}Ac/^{227}Th$ eq.	^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
		SK-Gd requirement →	<5	<0.5	<0.05	<0.05	<30	<30	-	-	-	-	-
17090X	Canfranc	ge-Asterix?	<12	<0.21	<0.30	<0.30	<0.42	<1.6	<1.0	<14	<0.13±0.03	<0.07	<0.13
180702	Canfranc	ge-Asterix	<6.2	<0.12	<0.22	<0.21	<0.3	<1.1	<0.5	0.13±0.04	<0.24±0.03	<0.07	<0.08
180703	Canfranc	ge-Asterix	<9.0	<0.24	<0.44	<0.38	<0.3	<1.1	<0.5	<0.14	<0.22±0.03	<<0.07	<<0.07
190302	Canfranc	ge-Asterix	<9.8	<0.32	<0.35	<0.29	<0.42	<0.92	<1.6	0.26±0.1	<0.21	<0.09	<0.09
190303	Canfranc	ge-Asterix	<8.4	<0.3	<0.44	<0.29	<0.39	<0.81	<1.5	0.45±0.09	0.16±0.12	<0.08	<0.09
190304	Canfranc	ge-Asterix	<11	<0.42	<0.55	<0.36	<0.52	<1.22	<2.1	0.40±0.11	<0.21	<0.13	<0.14
190502	Boulby	Belmont	<5.4	<0.49	<0.95	<0.48	<0.36	<1.7	<2.8	<0.28	0.49±0.08	-	<0.10
	Kamioka	Lab-C Ge	<25.0	<0.75	<0.52	<0.36	<9	7.9±0.8	<1.63	<0.37	0.68±0.18	<0.16	<0.22
190604	Boulby	Belmont	<9.80	<0.47	<0.61	<0.50	<0.45	<2.33	<2.45	<0.21	0.97±0.11	-	<0.08
	Kamioka	Lab-C Ge	<26.9	<0.68	<0.55	<0.33	<4.6	<1.2	<2.02	<0.36	1.43±0.19	<0.19	<0.34
190606	Boulby	Merrybent	<13.1	<0.84	<0.79	<0.63	<0.37	2.6±0.6	<3.27	<0.29	1.23±0.16	-	<0.13
	Kamioka	Lab-C Ge	<17.3	1.04±0.38	<0.91	<0.94	<8.3	2.6±1.3	<3.20	<0.26	0.74±0.29	<0.39	<0.50
	Kamioka	Lab-C Ge, Ra Disk	-	<0.31	<0.82	<0.48	-	-	-	-	-	-	-
190607	Canfranc	ge-Oroel	<7.2	<0.30	<0.79	<0.42	<0.30	<0.96	<1.59	<0.18	<0.13	<0.12	<0.09
190608	Canfranc	ge-Asterix	<8.8	<0.53	<0.43	<0.35	<0.40	<0.88	<1.50	<0.14	<0.25	<0.08	<0.09
	Kamioka	Lab-C Ge	<23.2	0.99±0.30	<1.38	<0.80	<4.3	<1.8	<2.15	<0.49	<0.51	<0.21	<0.30
	Kamioka	Lab-C Ge, Ra Disk	-	<0.63	<0.52	<0.61	-	-	-	-	-	-	-
190702	Canfranc	ge-Oroel	<11.0	<0.45	<1.11	<0.50	<0.37	2.4±0.9	<1.5	<0.20	0.23±0.13	<0.12	<0.11
	Kamioka	Lab-C Ge	<12.0	<0.63	<1.08	<0.33	<3.4	<1.6	<1.99	<0.28	0.28±0.12	<0.17	<0.28
190703	Canfranc	ge-Asterix	<8.4	<0.35	<0.51	<0.50	<0.45	1.8±1.0	<1.7	<0.20	0.51±0.13	<0.10	<0.10
190704	Boulby	Belmont	<9.8	[illegible]	[illegible]	[illegible]	<0.29	<1.39	<2.01	[illegible]	[illegible]	-	<0.10
190706	Boulby	Belmont	<9.5	<0.45	<0.66	0.53±0.12	<0.28	<1.32	<2.09	<0.25	<0.25	-	<0.13
	Kamioka	Lab-C Ge	<9.4	0.88±0.26	<0.50	<0.86	<0.26	<1.10	<1.9	<0.29	<0.19	<0.19	<0.26
190801	Canfranc	ge-Anayet	<28	0.39±0.32	<1.5	<0.77	<0.80	<1.17	<1.44	<0.18	2.7±0.2	<0.23	<0.18
190803	Canfranc	ge-Asterix	<7	<0.31	0.39±0.21	0.55±0.22	<0.36	<0.74	<1.4	<0.09	3.5±0.1	<0.08	<0.07
190804	Boulby	Belmont	<11	<0.46	0.67±0.21	<0.67	<0.38	<1.98	<2.57	<0.20	4.60±0.24	-	<0.10
190805	Canfranc	ge-Oroel	<9.3	<0.52	0.53±0.44	0.57±0.40	<0.44	<0.98	<1.18	<0.10	9.44±0.10	<0.10	<0.09
190806	Boulby	Merrybent	<8.09	<0.43	0.49±0.11	1.27±0.13	<0.26	<1.23	<1.78	<0.14	9.35±0.22	-	<0.07
190901	Canfranc	ge-Asterix	<8.6	<0.30	0.42±0.27	0.37±0.27	<0.46	<1.20	<1.47	<0.15	4.85±0.12	<0.10	<0.13
190902	Boulby	Belmont	<5.52	<0.26	0.53±0.10	0.63±0.09	<0.33	<1.22	<1.32	<0.10	8.78±0.18	-	<0.05
190903	Canfranc	ge-Asterix	<8.9	<0.37	0.59±0.28	0.35±0.28	<0.54	<1.7	<1.5	<0.14	4.9±0.1	<0.10	<0.09
190905	Kamioka	Lab-C Ge	<8.6	<0.21	0.72±0.20	0.70±0.16	<5.2	<1.1	<1.57	<0.09	6.6±0.2	<0.09	<0.13
	Kamioka	Lab-C Ge, Ra Disk	-	<0.29	0.58±0.25	<0.39		-	-		-	-	-
200101	Kamioka	IPMU-N	<87	<2.8	<4.0	<2.5	<18	<4.5	<67	-	5.2±0.9	-	<1.2
200103	Kamioka	IPMU-N	<114	<2.4	<7.7	<2.4	<17	<4.1	<19	-	<0.91	-	<1.0
200104	Kamioka	IPMU-P	<95.1	<2.8	<3.0	<2.8	<15	<9.0	<31		<0.82	-	<0.64

ICPMS results



Basically OK

- first half of production: batch purities OK
- latter half: one order of magnitude more ^{228}Ra than specs. Correlated with an intrinsically large contaminations in raw Gd_2O_3 (well above the typical ~200 ppb, ^{176}Lu also seen)
- Increase of background solar-**ν** candidates from this ^{228}Ra, similar as cand. in pure water phases of SK:
  - → To SK but, any future loading in SK will have the $Gd_2(SO_4)_3 \cdot 8H_2O$ free of that contamination.
  - → new method to remove the ^{228}Ra (from Gd_2O_3) recently established

see the soon-to-be-published publication with all these works

A summary of HPGe and ICP-MS meas. on all $Gd_2(SO_4)_3 \cdot 8H_2O$ batches for T1 phase of SK-Gd

- The total SK-Gd radioactivity budget is estimated for a 0.2% loading (130 tonnes of $Gd_2(SO_4)_3 \cdot 8H_2O$)
- When finite activities are obtained: extrapolate to the total mass dissolved ***in their corresponding batches*** and add these statistically → **FM**
- When only upper limits are obtained: extrapolate to the total mass dissolved in their corresponding batches and add these → **UL**

Chain	Part of Chain	$t_{1/2}$	SK-Gd Requirements		HPGe		ICP-MS
			Specific Activity (mBq/kg)	total budget (Bq)	**FM** (Bq)	**UL** (Bq)	Total (Bq)
^{238}U	^{238}U	4.5 Gy	< 5	650	0.0 ± 1.1	< 260	0.34 ± 0.15
	^{226}Ra	1602 y	< 0.5	65	0.76 ± 0.20	< 8.9	–
^{232}Th	^{232}Th	14 Gy	< 0.05	6.5	–	–	0.25 ± 0.07
	^{228}Ra	5.7 y	< 0.05	6.5	2.16 ± 0.33	< 15.5	–
	^{228}Th	1.9 y	< 0.05	6.5	2.38 ± 0.28	< 10.8	–
^{235}U	^{235}U	0.7 Gy	< 30	3900	0.0 ± 1.1	< 32	–
	^{227}Ac	21.7 y	< 30	3900	3.3 ± 1.1	< 26	–

Additional procedures in the purification process were needed [and successfully achieved for phase T1.5 t.b.p.]

Summary / Conclusions / Outlook

- 13.2 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ (Gd salt) dissolved into Super Kamiokande in 2020 (SK Gd phase T1)

- impact of radioactive impurities in the Gd salt on DSNB search and solar-ν observation studied:
  → must reduce RI levels by ~3 orders of magnitude from commercially available Gd salt;
  → a method to remove impurities from Gd_2O_3 was successfully developed.

- All the produced Gd salt was screened. Because of the low RI levels we need to use ICP-MS and HPGe
  → HPGe measurements require a long time to obtain sufficient sensitivity
  → establish cooperation among best HPGe det. at Boulby (UK), LSC (Spain), and Kamioka (Japan)

- first half of production OK. Second half: one order of magnitude more ^{228}Ra than maximum
  → Increase of bkg solar-ν candidates from this ^{228}Ra, similar as bkg. in pure water phases of SK:
  → dissolve into SK BUT, any future loading in SK will have the Gd salt free of that contamination.
  → new method to remove the ^{228}Ra (from Gd_2O_3) recently established

- The 26 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ currently being introduced into SK (SK Gd phase T1.5) are showing, for the time being, the required high-purity.

additional

Sample	Laboratory	Detector / Method	Activity (mBq/kg, 95% c.l.)										
			^{238}U		^{232}Th		^{235}U		^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
			^{238}U eq.	^{226}Ra eq.	^{228}Ra eq.	^{228}Th eq.	^{235}U eq.	^{227}Ac/^{227}Th eq.					
		SK-Gd requirement →	<5	<0.5	<0.05	<0.05	<30	<30	-	-	-	-	-
17090X	Canfranc	ge-Asterix?	<12	<0.21	<0.30	<0.30	<0.42	<1.6	<1.0	<14	<0.13±0.03	<0.07	<0.13
180702	Canfranc	ge-Asterix	<6.2	<0.12	<0.22	<0.21	<0.3	<1.1	<0.5	0.13±0.04	<0.24±0.03	<0.07	<0.08
180703	Canfranc	ge-Asterix	<9.0	<0.24	<0.44	<0.38	<0.3	<1.1	<0.5	<0.14	<0.22±0.03	<<0.07	<<0.07
190302	Canfranc	ge-Asterix	<9.8	<0.32	<0.35	<0.29	<0.42	<0.92	<1.6	0.26±0.1	<0.21	<0.09	<0.09
190303	Canfranc	ge-Asterix	<8.4	<0.3	<0.44	<0.29	<0.39	<0.81	<1.5	0.45±0.09	0.16±0.12	<0.08	<0.09
190304	Canfranc	ge-Asterix	<11	<0.42	<0.55	<0.36	<0.52	<1.22	<2.1	0.40±0.11	<0.21	<0.13	<0.14
190502	Boulby	Belmont	<5.4	<0.49	<0.95	<0.48	<0.36	<1.7	<2.8	<0.28	0.49±0.08	-	<0.10
	Kamioka	Lab-C Ge	<25.0	<0.75	<0.52	<0.36	<9	7.9±0.8	<1.63	<0.37	0.68±0.18	<0.16	<0.22
190604	Boulby	Belmont	<9.80	<0.47	<0.61	<0.50	<0.45	<2.33	<2.45	<0.21	0.97±0.11	-	<0.08
	Kamioka	Lab-C Ge	<26.9	<0.68	<0.55	<0.33	<4.6	<1.2	<2.02	<0.36	1.43±0.19	<0.19	<0.34
190606	Boulby	Merrybent	<13.1	<0.84	<0.79	<0.63	<0.37	2.6±0.6	<3.27	<0.29	1.23±0.16	-	<0.13
	Kamioka	Lab-C Ge	<17.3	1.04±0.38	<0.91	<0.94	<8.3	2.6±1.3	<3.20	<0.26	0.74±0.29	<0.39	<0.50
	Kamioka	Lab-C Ge, Ra Disk	-	<0.31	<0.82	<0.48	-	-	-	-	-	-	-
190607	Canfranc	ge-Oroel	<7.2	<0.30	<0.79	<0.42	<0.30	<0.96	<1.59	<0.18	<0.13	<0.12	<0.09
190608	Canfranc	ge-Asterix	<8.8	<0.53	<0.43	<0.35	<0.40	<0.88	<1.50	<0.14	<0.25	<0.08	<0.09
	Kamioka	Lab-C Ge	<23.2	0.99±0.30	<1.38	<0.80	<4.3	<1.8	<2.15	<0.49	<0.51	<0.21	<0.30
	Kamioka	Lab-C Ge, Ra Disk	-	<0.63	<0.52	<0.61	-	-	-	-	-	-	-
190702	Canfranc	ge-Oroel	<11.0	<0.45	<1.11	<0.50	<0.37	2.4±0.9	<1.5	<0.20	0.23±0.13	<0.12	<0.11
	Kamioka	Lab-C Ge	<12.0	<0.63	<1.08	<0.33	<3.4	<1.6	<1.99	<0.28	0.28±0.12	<0.17	<0.28
190703	Canfranc	ge-Asterix	<8.4	<0.35	<0.51	<0.50	<0.45	1.8±1.0	<1.7	<0.20	0.51±0.13	<0.10	<0.10
190704	Boulby	Belmont	<9.8	<0.44	<0.66	<0.75	<0.29	<1.39	<2.01	<0.25	<0.18	-	<0.10
190706	Boulby	Belmont	<9.5	<0.45	<0.66	0.53±0.12	<0.28	<1.32	<2.09	<0.25	<0.25	-	<0.13
	Kamioka	Lab-C Ge	<9.4	0.88±0.26	<0.50	<0.86	<2.26	<1.10	<1.9	<0.29	<0.19	<0.19	<0.26
190801	Canfranc	ge-Anayet	<28	0.39±0.32	<1.5	<0.77	<0.80	<1.17	<1.44	<0.18	2.7±0.2	<0.23	<0.18
190803	Canfranc	ge-Asterix	<7	<0.31	0.39±0.21	0.55±0.22	<0.36	<0.74	<1.4	<0.09	3.5±0.1	<0.08	<0.07
190804	Boulby	Belmont	<11	<0.46	0.67±0.21	<0.67	<0.38	<1.98	<2.57	<0.20	4.60±0.24	-	<0.10
190805	Canfranc	ge-Oroel	<9.3	<0.52	0.53±0.44	0.57±0.40	<0.44	<0.98	<1.18	<0.10	9.44±0.10	<0.10	<0.09
190806	Boulby	Merrybent	<8.09	<0.43	0.49±0.11	1.27±0.13	<0.26	<1.23	<1.78	<0.14	9.35±0.22	-	<0.07
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190905	Kamioka	Lab-C Ge	<8.6	<0.21	0.72±0.20	0.70±0.16	<5.2	<1.1	<1.57	<0.09	6.6±0.2	<0.09	<0.13
	Kamioka	Lab-C Ge, Ra Disk	-	<0.29	0.58±0.25	<0.39	-	-	-	-	-	-	-
200101	Kamioka	IPMU-N	<87	<2.8	<4.0	<2.5	<18	<4.5	<67	-	5.2±0.9	-	<1.2
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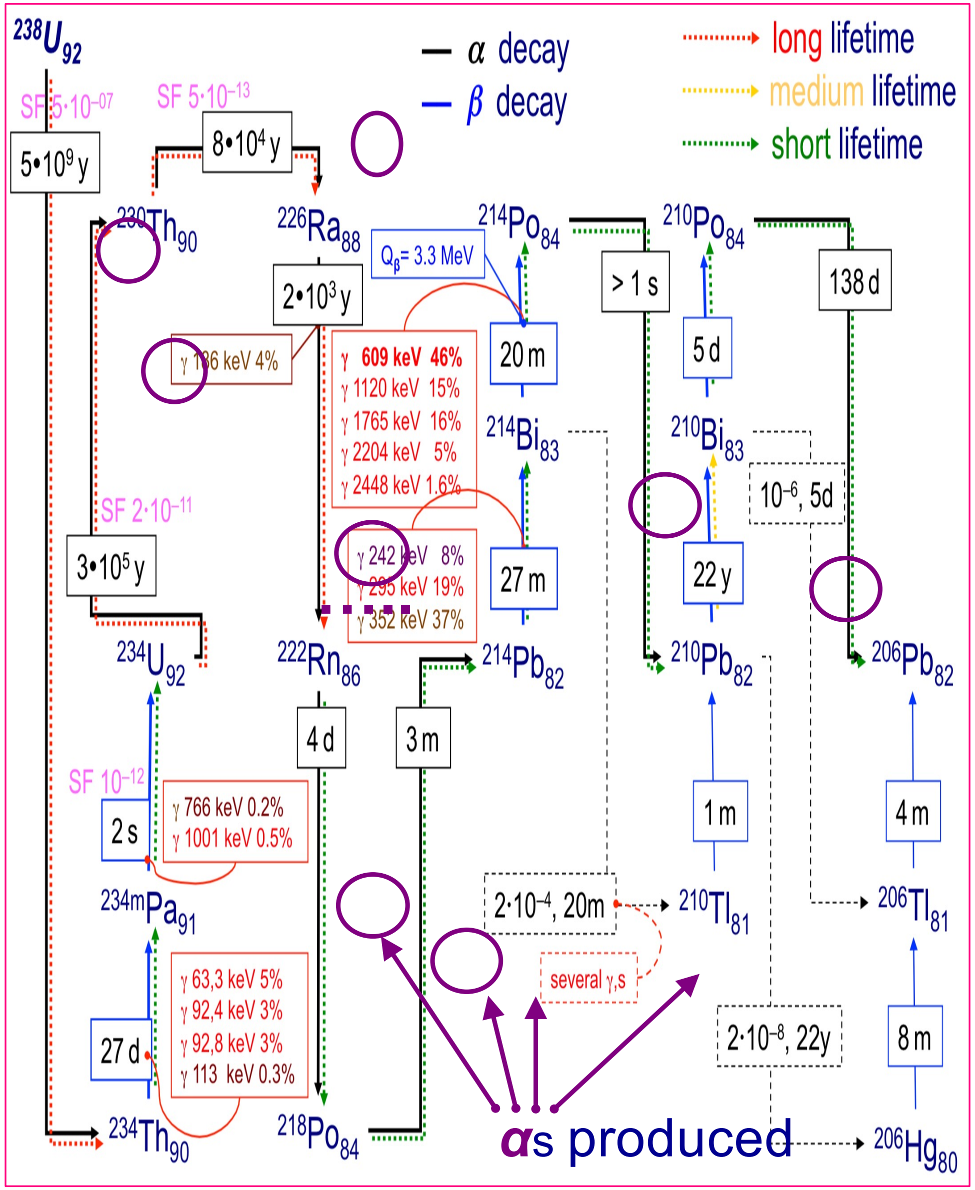
200104	Kamioka	IPMU-P	<95.1	<2.8	<3.0	<2.8	<15	<9.0	<31	-	<0.82	-	<0.64

neutrons

- there are many, naturally produced
- relevant are neutrons produced from α decays in the naturally present radioactive chains
  - for instance that of ^{238}U
  - αs interact with the water :



$$^{18}O+{}^{4}\alpha(\sim 6MeV)\rightarrow {}^{22}Ne^*[\sim 15MeV]\rightarrow$$

$$\text{X} \dashrightarrow {}^{22}Ne+\gamma \qquad \qquad \text{X} \dashrightarrow {}^{21}Ne+n+\gamma$$

$$\rightarrow {}^{21}Ne^*[\sim 12.5MeV]+n(\sim 2.5MeV)\rightarrow {}^{20}Ne+2\cdot n(\sim 2.3MeV)$$

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Main radiation produced by RI: neutrons

example from ^{232}Th, ^{235}U, ^{238}U chains in SuperK-Gd for "market standard" $Gd_2(SO_4)_3$

- relatively high RI levels (see later)
- computed with SOURCES4C
- dominated by (α,n) reactions on oxygen ^{18}O
- multiplicity of two in them
- for the radioactivity levels taken $5.1 \cdot 10^{-13}$ neutrons/s/cm^3

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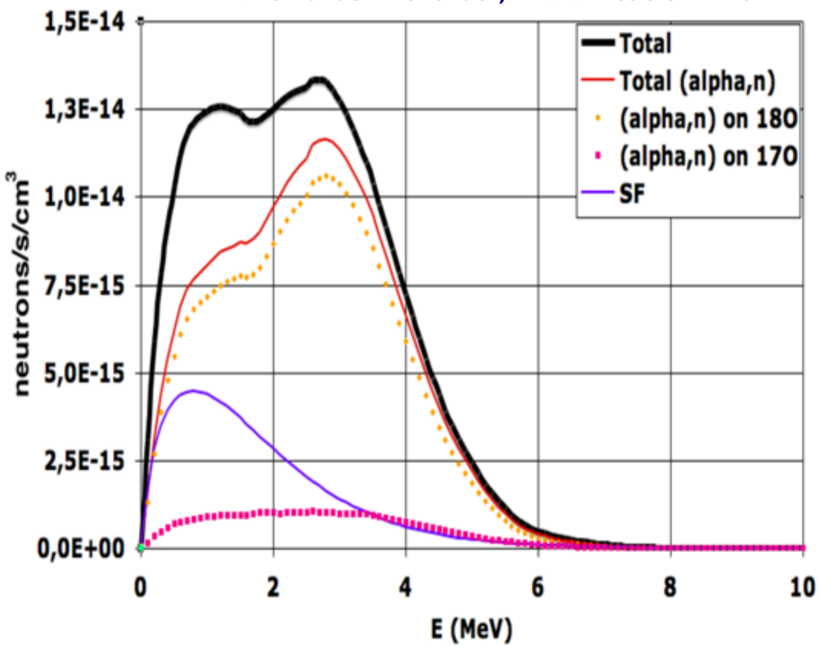

$$N_{rad}^{neutrons} = 316.3 \frac{single\ neutrons}{day \cdot SKFV}$$